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16. ABSTRACT

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GAC Treatment Costs: A Sensitivity Analysis

By Robert M. Clark,[1] M. ASCE, Richard G. Eilers,[2] and Benjamin W. Lykins, Jr.[3]

Abstract: Although admittedly effective for removing organic compounds, concerns have been raised about the cost of using GAC for treating drinking water. This paper is devoted to the discussion of the cost of granular activated carbon for removing organic compounds from drinking water. Activated carbon has been shown to be effective for removing a broad spectrum of organics from drinking water (VOC's, SOC's, TOC, etc.) but is most effective for removing high molecular weight compounds. The costs developed in this paper coupled with the proper performance relationships should be useful for all of these applications. Extensive cost sensitivity analysis is performed. Several variables are identified as being important. These include choice of system configuration, loading rate and size of system, reactivation frequency, interest rate and design life of system, local construction and operating costs and carbon use rate.

Introduction

On February 9, 1978, the Environmental Protection Agency (EPA) proposed a regulation designed to protect the public health from organic chemical contaminants in drinking water (3). Originally, the regulation consisted of two parts: Part A, proposing a maximum contaminant level (MCL) of 0.10 mg/L (100 ug/L) for total trihalomethanes (TTHM) including chloroform; and Part B, a treatment technique requiring the use of granular activated carbon (GAC) to remove synthetic organic chemicals in surface waters associated with industrial pollution and urban and agricultural runoff. Part A was promulgated as proposed on November 29, 1979, and Part B was eliminated in large part because of the objections raised by the American Water Works Association and many of its member utilities. At the time of the original proposal most attention was focused on issues related to the cost of GAC treatment.

Cost data used in this paper are taken from a report prepared by the Drinking Water Research Division (DWRD) and completed by Culp/Wesner/Culp (C/W/C) Consulting Engineers, that developed operating costs for water treatment processes sufficiently accurate for preliminary planning and flexible enough for cost effectiveness studies (2). Capital and operation and maintenance (O&M) costs were developed for a series of unit processes. The capital and O&M cost for each unit process is presented as a function of a given process design parameter.

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Zurheide-Herman, a cost-estimating firm, reviewed the costs developed by C/W/C.

The C/W/C study focused on: (1) Processes for removing from potable water those contaminants included in the National Interim Primary Drinking Water Regulations (NIPDWR); and (2) development of construction and operation and maintenance cost curves. The final data base contained cost curves for 99 unit processes and a computer program for retrieving, updating, and combining the cost data (2).

Because cost is an important factor in choosing a treatment technology, the authors have developed a series of equations based on the original data base that, coupled with appropriate performance information, can be useful for estimating GAC treatment costs (VOC's and SOC's). These equations are particularly useful for assessing the sensitivity of costs to changes in various design parameters.

TABLE 1.—Design Parameters for Granular Activated Carbon Using On-Site Multiple Hearth Reactivation

Design parameter (1)	Level (2)
Sand replacement:	
Activated carbon cost	$0.70/lb ($1.54/kg)
Activated carbon loss per reactivation cycle	10%
Fuel cost	$3.60/million BTU ($3.41 th J)
Electric power cost	$0.05/kw hr
Construction cost index	365.97
Producers price index	285.10
Direct hourly wage rate	$9/hr
Amortization rate	10%
Amortization period	20 yr
Volume per filter	856 ft^3 (24 m^3)
Loss in adsorptive capacity	0%
Design capacity	70%
Empty bed contact time	9 min
Reactivation frequency	Every 1.2 months
Post-filter adsorption	
Activated carbon cost	$0.70/lb ($1.54/kg)
Activated carbon loss per reactivation cycle	6%
Fuel cost	$3.60/million BTU (3.41 th J)
Electric power cost	$0.05/kw hr
Construction cost index	365.97
Producers price index	285.10
Direct hourly wage rate	$9/hr
Amortization rate	10%
Amortization period	20 yr
Loss in adsorptive capacity	0%
Design capacity	70%
Empty bed contact time	18 min
Reactivation frequency	Every 2.4 months

Equation Development

Using data generated from the aforementioned data base, several types of equations are developed using regression analysis. Each form of equation selected for use in the analysis is designed to reflect the characteristics of the type of cost being studied. As will be described in the following sections total, O&M and capital costs and their relationship to such system variables as hydraulic loading, design capacity, amortization period and carbon reactivation frequency are examined. The effect of varying individual O&M and capital cost variables such as labor wage rate and power costs, holding the remaining variables constant are also examined.

In the following section a "base case" is presented in which unit costs for a specific set of design assumptions are calculated. The equations developed in this study can be used to examine the sensitivity of the costs in the "base case" to changes in the level of the operating and system variables.

This economic analysis will include both the use of GAC as a replacement for existing filtration media (sand replacement) and as a separate adsorption system (post-sand filter adsorption) (6). The primary focus of this analysis is on separate adsorption systems and on-site multiple hearth reactivation. Key design parameters are set at predetermined levels and then one variable at a time is changed to determine its effect on cost. Tables 1 and 2 contain basic design assumptions for both post-filter adsorption and sand replacement. The need to consider the cost of separate GAC contactors is eliminated if GAC is assumed to replace sand in existing filters. For purposes of the sand replacement analysis, a water treatment plant is assumed to consist of an integral number of 1-MGD (3,800 m^3/d), filters with an effective volume of 18.5′ (5.6 m) × 18.5′ (5.6 m) × 2.5′ (0.8 m) or 856 ft^3 (24.4 m^3). Design parameters assumed for the sand replacement systems are shown in Table 1, and design assumptions for post-filter adsorber systems are shown in Tables 1 and 2.

The physical design values in Tables 1 and 2 are the same as those

TABLE 2.—Assumptions for Post-Sand Filter GAC Adsorption

Item (1)	Design Capacity—MGD, in Cubic Meters per Day[a]				
	1 (3,800) (2)	5 (19,000) (3)	10 (38,000) (4)	100 (380,000) (5)	150 (568,000) (6)
Number of contactors	3	6	12	40	60
Diameter of contactors—ft (m)	8 (2.4)	12 (3.7)	12 (3.7)	20 (6.1)	20 (6.1)
Depth of contactors—ft (m)	13 (4.0)	13 (4.0)	13 (4.0)	14 (4.3)	14 (4.3)
Volume of GAC per contactor—ft^3 (m^3)	653.1 (18.5)	1,469.5 (41.6)	1,469.5 (41.6)	4,396.0 (124.4)	4,396.0 (124.4)
Minimum empty bed contact time–min	18	18	18	18	18

[a]¢/1,000 gal × 0.26 = ¢/m^3.

TABLE 3.—Amortized Capital and O&M Costs for GAC Systems with On-Site Multiple Hearth Reactivation (¢/1,000 Gal)*

Description (1)	PLANT CAPACITY—MGD, IN CUBIC METERS PER DAY									
	1 (3,800)		5 (19,000)		10 (38,000)		100 (380,000)		150 (568,000)	
	Capital (2)	O&M (3)	Capital (4)	O&M (5)	Capital (6)	O&M (7)	Capital (8)	O&M (9)	Capital (10)	O&M (11)
Sand Replacement										
Reactivation	47.0	16.3	14.3	9.4	9.8	8.4	2.8	6.6	2.2	6.4
Activated carbon	4.7	0.0	3.3	0.0	3.0	0.0	2.6	0.0	0.0	0.0
Total	51.7	16.3	17.6	9.4	12.8	8.4	5.4	6.6	4.8	6.4
Filter-Adsorbers										
Reactivation	50.3	17.5	14.5	8.5	9.8	7.4	2.8	5.6	2.5	5.5
Contactor	6.6	4.9	5.3	2.2	5.2	1.7	4.5	1.1	4.4	1.0
Activated carbon	3.1	0.0	2.7	0.0	2.6	0.0	2.6	0.0	2.5	0.0
Total	60.0	22.4	22.5	10.7	17.6	9.1	9.9	6.7	9.4	6.5

*To convert from ¢/1,000 gal to ¢/m^3 multiply by 0.26.

used in earlier cost evaluations and chosen so that this more current cost analysis, using updated economic variables, could be compared with previous calculations (3). Values were chosen to reflect the differences in operation of post-filter and sand replacement systems. Losses of 6% and 10% were chosen, respectively, to approximate the increased handling of carbon in a sand replacement system. Reactivation cycles of 2.4 and 1.2 months were chosen because the contact time in the post-filter design is twice that of the sand replacement system and it is assumed that this combination of reactivation frequency and contact time would provide each configuration with comparable finished water targets.

Because much of the capital investment in both post GAC adsorption and sand replacement is in furnace technology when the GAC is reactivated on-site, special attention was paid to selection of furnace designs. All of the costs presented in Table 3 are based on the following fixed furnace hearth areas: 27; 37; 147; 359; 732; and 1,509 ft^2 (2.5; 34; 13.7; 33.4; 68.0; and 140.2 m^2). It should be noted that many small systems [<10 mgd (38,000 m^3/day)] might not use on-site reactivation.

Table 3 shows the unit costs for both sand replacement and post-filter adsorption systems for 1, 5, 10, 100, and 150 MGD plants (3,800, 19,000, 38,000, 380,000 and 568,000 m^3/d) at 70% capacity (ratio of average use to design capacity). Table 3 shows that a large portion of the capital cost for both processes is associated with reactivation. The percentage impact of reactivation cost is greater for sand replacement than for post-filter adsorbers. Post-filter GAC adsorption is more capital intensive in general than is the sand replacement mode.

Sensitivity Analysis

In this section, the effect of changing variable levels will be considered. The values shown in Table 1, yielding the unit costs shown in Table 3 will be assumed as a base case. The effect of changing the design parameters around the standardized values is examined for GAC sand

replacement and post-filter adsorbers separately. In the following sections equations will be developed that allow for sensitivity analysis of the effect of design variables on overall system cost. These design variables include hydraulic loading, design capacity, reactivation frequency and amortization period. Equations are also developed that show the effect of changing selected operating and capital cost variables such as carbon cost, hourly wage rate, interest rate, etc.

System Design Costs

Post-filter and sand replacement equations are developed for the following conditions: post-filter and sand replacement assuming fixed reactivation cycles and loading factors but with variable design capacity; assumed fixed reactivation cycle but variable hydraulic loading and design capacity; assumed fixed hydraulic loading but variable design capacity and reactivation cycle. In addition equations assuming fixed design capacity but variable amortization period are developed for post-filter adsorption.

Variable Design Capacity.—Eq. 1 shows the equation form chosen to relate cost to capacity:

$$Y = KQ^a \quad \ldots\ldots (1)$$

in which Y = unit cost (O&M, capital or total); a and K = constants to be determined from regression; and Q = design capacity of facility.

Fig. 1 shows the total production cost for both sand replacement and post-filter adsorption systems versus plant capacity (holding other variables constant), based on the assumptions in Tables 1 and 2. Eq. 2 [Table 4 (Eqs. 2–7)] describes the relationship for sand replacement shown in Fig. 1, and Eq. 3 describes the relationship for post filter adsorbers. Eqs. 4–7 show these same relationships for operating and maintenance and capital cost.

In the following sections equation forms are used that reflect the effect

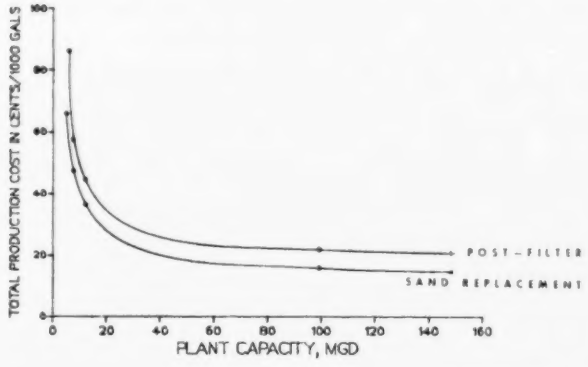

FIG. 1.—Total Production Cost versus Plant Capacity for Post-Filter Adsorption and Sand Replacement

TABLE 4.—Equations Relating Cost to System Variables

Y (1)	K (2)	a (3)	Equation number (4)
Total production[a,b] cost in ¢/1,000 gal for sand replacement	55.2	−0.34	2
Total production[c,d] cost in ¢/1,000 gal for post-filter adsorbers	66.1	−0.31	3
O&M cost for sand[a,b] replacement in ¢/1,000 gal	13.9	−0.20	4
O&M cost for[c,d] post-filter adsorbers in ¢/1,000 gal	18.8	−0.24	5
Capital cost for[a,b] sand replacement in ¢/1,000 gal	43.3	−0.47	6
Capital cost for[c,d] post-filter adsorbers in ¢/1,000 gal	47.7	−0.36	7

[a]Assumes 70% capacity.
[b]Assumes a reactivation frequency of 1.2 months.
[c]Assumes 70% capacity.
[d]Assumes a reactivation frequency of 2.4 months.

of varying both design capacity and one other variable (hydraulic loading and reactivation frequency). These equations are developed in the following sections.

Impact of Hydraulic Loading.—To show the impact of both hydraulic loading and design capacity the following equation was used (see Eq. 2):

$$Y = KQ^bL^c \quad \ldots\ldots\ldots\

based on this assumption. Eq. 13 shows the relationships between design capacity and reactivation frequency:

$$Y = KQ^bR^c \quad \ldots\ldots (13)$$

in which Y = unit cost (O&M, capital and total); b, c, K = constants to

TABLE 6.—Cost Equations for Reactivation Period*

Y (1)	K (2)	b (3)	c (4)	Equation number (5)
Total production cost	101.88	−0.30	−0.36	14
O&M cost	34.99	−0.23	−0.61	15
Capital cost	65.74	−0.35	−0.22	16

*Assumes post filters with a load factor of 70%.

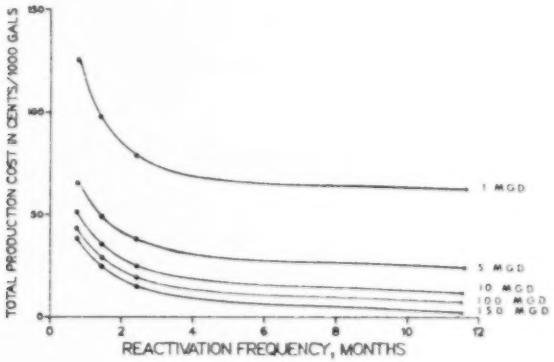

FIG. 2.—Total Production Cost versus Reactivation Frequency for Post-Filter Adsorption

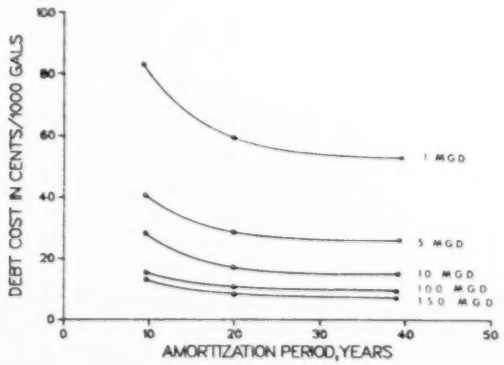

FIG. 3.—Debt Cost versus Amortization Period for Post-Filter Adsorption

be determined from regression; and R = period between reactivations in month.

Table 6 contains the parameters for this equation and Fig. 2 illustrates the effect of reactivation frequency on total production cost.

Impact of Amortization Period.—Amortization period can have a significant effect on capital cost as shown in Fig. 3. Eq. 17 relates the effect of amortization period on capital cost for post-filter adsorption:

$$Y = 147.33 Q^{-0.34} AP^{-0.33} \quad \ldots\ldots (17)$$

in which Y = debt cost in ¢/1,000 gal; Q = design capacity (70% of capacity); and AP = amortization period in years. As can be seen, the impact of changing these parameters is greater for small than large plants.

Linear Variables

Some costs tend to vary directly with the value of the cost variable so that for a given system size the descriptive equation is linear. Often the slope and intercept of the cost function varies with system size. Therefore for this class of variable, the following equation form was used:

$$Y = K_1 Q^a + K_2 Q^b X \quad \ldots\ldots (18)$$

TABLE 7.—O&M Cost Equations (70% Capacity)

X (1)	K_1 (2)	K_2 (3)	a (4)	b (5)	Equation number (6)
Hourly wage rate in $/hr	13.38	0.58	−0.20	−0.34	19
Carbon loss per reactivation cycle (%)	16.85	0.32	−0.27	−0.03	20
Fuel cost in $/therm	12.99	15.36	−0.27	−0.14	21
Producers price index	15.98	0.01	−0.26	−0.09	22
Electric power cost in $/kWhr	13.29	104.95	−0.19	−0.35	23

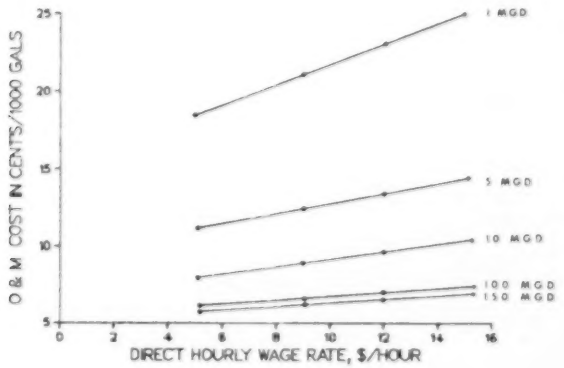

FIG. 4.—O&M Cost versus Wage Rate for Post-Filter Adsorption

TABLE 8.—Capital Cost Equations (70% Capacity)

X (1)	K_1 (2)	K_2 (3)	a (4)	b (5)	Equation number (6)
Engineering construction cost index	0.20	0.14	−0.47	−0.34	24
Interest rate, as a percentage	16.14	3.69	−0.47	−0.31	25

in which Y = unit cost (capital or O&M); K_1, a, K_2, b = constants; Q = design capacity; nd X = operating variable (wage rate, power cost, interest rate, etc.).

O&M Cost Effects.—The first set of variables to be examined are those that affect only O&M cost: hourly wage rate in $/hr; activated carbon loss per reactivation cycle in %; fuel cost in $/therm; producers price index; and electrical power cost in $/kwh. This analysis is performed for

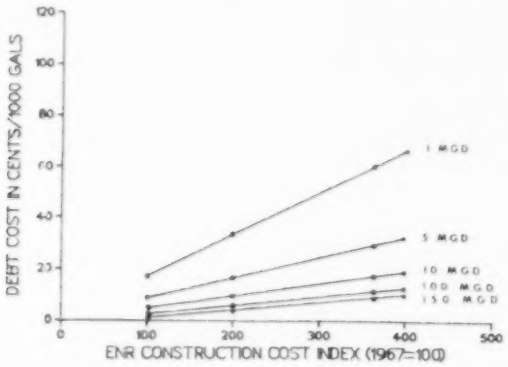

FIG. 5.—Debt Cost versus Construction Cost Index for Post-Filter Adsorption

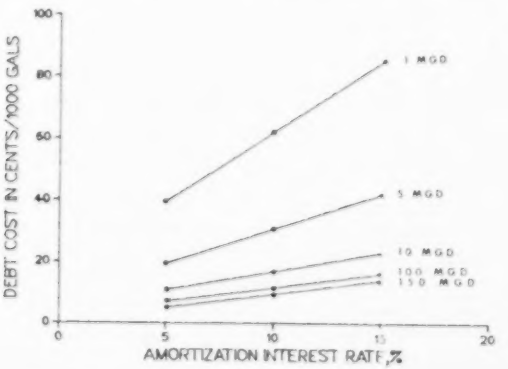

FIG. 6.—Debt Cost versus Interest Rate for Post-Filter Adsorption

TABLE 9.—O&M and Capital Cost Equations (70% Capacity)

X (1)	K_1 (2)	K_2 (3)	a (4)	b (5)	Equation number (6)
Carbon cost, in $/lb (O&M)	16.60	2.86	−0.29	−0.00176	26
Carbon cost, in ¢/lb (capital)	49.09	2.86	−0.38	−0.00214	27

Note: (¢/1,000 gal).

1, 5, 10, 100 and 150 mgd (4,000, 19,000, 38,000, 380,000 and 568,000 m^3) systems operating at 70% of capacity. The equations are summarized in Table 7.

Fig. 4 shows that changes in hourly wage rate have a greater impact on O&M cost in small plants than in larger plants. For example, it can be seen that as the hourly wage rate increases from $6/hr to $10/hr, the O&M cost for one mgd (3,800 m^3) plant increases from slightly over 19¢/1,000 gal (4.9 ¢/m^3) to slightly less than 22¢/1,000 gal (5.7 ¢/m^3). The same wage rate changes in a 10 mgd (38,000 m^3) plant increases the O&M cost from approximately 8¢/1,000 gal (2.1 ¢/m^3) to 9¢/1,000 gal (2.3 ¢/m^3).

Capital Cost Effect.—The group of variables that influence amortized capital cost are as follows: construction cost index; amortization interest rate; amortization period in years. These results are shown in Table 8.

Fig. 5 illustrates the impact of the variation of construction cost index on amortized capital cost in ¢/1,000 gal. Fig. 6 shows the effect of changing interest rates on amortized capital cost.

O&M and Capital Cost Effect.—Several of the standard design parameters affect both amortized capital and O&M cost. These parameters are activated carbon cost and reactivation frequency. Table 9 contains the results of this analysis.

Design Implications

The sensitivity analysis performed in the previous sections suggests some important design implications. Based on this analysis and because of the capital intensive nature of post filter adsorbers any variation in design that can use invested capital more efficiently should be explored. To illustrate these possibilities the following examples will be considered: trade-off between contractor volume and number of contactors; activated carbon quality and cost; and contact time and activated carbon use rate.

Contactors—Volume and Number.—If a constant total volume is to be maintained, minimum cost will result from fewer contactors of larger volume. The cost for additional increments of volume in a given contactor is lower than for adding additional numbers of contactors. To illustrate this effect, assume two design configurations for contactors and volume as shown in Table 10. Fig. 7 is a plot based on the values in Table 10. Configurations with fewer contactors and larger volumes (Design 2) are always less expensive even though the total volume of activated carbon is the same for both design configurations.

TABLE 10.—Assumed Design Configurations for GAC Contactors

Item (1)	Number of contactors (2)	Volume per contactor, in cubic feet (cubic meters) (3)	Total contactor volume, in cubic feet (cubic meters) (4)	Annual capital cost, in dollars per year (5)
1[a]	6	1,500 (42.5)	9,000 (225.0)	99,000
2[b]	3	3,000 (84.9)	9,000 (255.0)	89,000
1	12	1,500 (42.5)	18,000 (510.0)	194,000
2	6	3,000 (84.9)	18,000 (510.0)	174,000
1	40	4,400 (124.5)	176,000 (4,980.0)	1,656,000
2	20	8,800 (249.0)	176,000 (4,980.0)	1,487,000
1	60	4,400 (124.5)	264,000 (7,470.0)	2,519,000
2	30	8,800 (249.0)	264,000 (7,470.0)	2,260,000

[a]More contactors of smaller volume.
[b]Fewer contactors of larger volume.

The equations that describe these costs are

$$D_1 = 14.94 S^{0.96} \quad \ldots\ldots (28)$$

$$D_2 = 13.26 S^{0.96} \quad \ldots\ldots (29)$$

in which D_1 = annual capital cost for design 1 in \$/yr (10%, 20 yr); D_2 = annual capital cost for design 2 in \$/yr (10%, 20 yr); and S = volume of contactors in cubic feet.

Carbon Cost and Quality.—The previous analysis shows that carbon

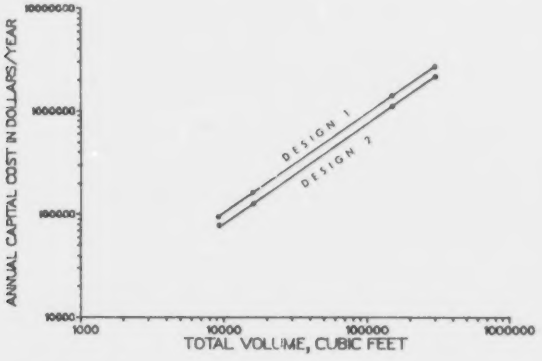

FIG. 7.—Comparison between Design Configurations

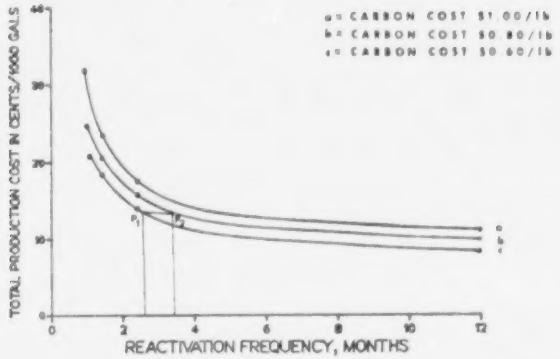

FIG. 8.—Total Production Cost versus Reactivation Frequency for Post-Filter Adsorption

cost, carbon loss and reactivation frequency have a significant impact on costs. A manager interested in minimizing total system cost might choose to purchase the minimum cost activated carbon. However the minimum cost carbon may have lower capacity and thus require more frequent reactions to meet a given quality target. Fig. 8 shows total system costs versus reactivation frequency for a 100 mgd (380,000 m^3) post-filter adsorption system (70% capacity) for three different carbon costs. Assuming 60¢/lb (132.3 ¢/kg) carbon for the system being reactivated at a frequency of 2.7 months, the total system cost is approximately 16¢/1,000 gal @ P_1 (4.2¢/m^3). If carbon cost is increased from 60¢/lb (132.3¢/kg) to 80¢/lb (176.4¢/kg), the reactivation period would have to increase from 2.7–3.4 months (P_2) for costs to remain constant. If the reactivation period increased beyond 3.4 months as a result of the more expensive carbon, system cost would be lowered. For example, if the cost of activated carbon increased by 33%, the reactivation rate (lb/day) has to decrease on the average by 25% or correspondingly the period between reactivations has to increase by 25%. If one wishes to use a more expensive carbon, the decrease in reactivation frequency and activated carbon loss, or both, must be sufficiently great to off-set the increased cost.

The equation that describes this relationship is:

$$Y = 28.39C^{0.23}R^{-0.37} \quad \ldots\ldots\ldots\

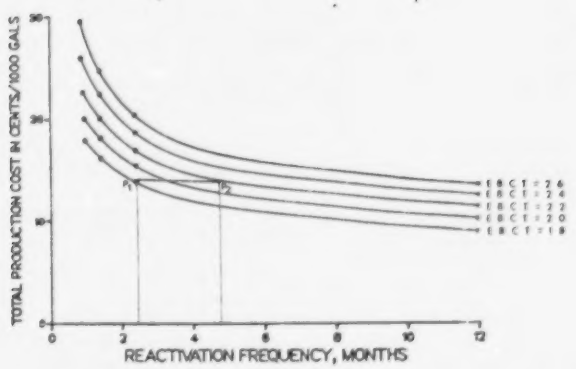

FIG. 9.—Effect of Changing Empty Bed Contact Time on Total Production Cost

(70% capacity). From Fig. 9, if the required EBCT of 18 min at a reactivation frequency of 2.4 months were increased to 22 min, the reactivation period would have to be increased to 4.2 months (P_2) or greater to achieve a favorable economic trade-off. Therefore, to maintain the same cost if the EBCT were increased by 22%, the period between reactivations would have to increase by at least 75%.

The equation that describes this relationship is:

$$Y = 1.63\,\mathrm{EBCT}^{0.87} R^{-0.29} \quad \ldots\ldots\ldots\

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Appendix II.—Notation

The following symbols are used in this paper:

AP = amortization period years;
CC = carbon cost in \$/lb;
D_1 = annual capital cost for design 1 in \$/yr;
D_2 = annual capital cost for design 2 in \$/yr;
EBCT = empty bed contact time in minutes;
K_1, K_2, K, a, b, c = constants to be determined by regression;
L = load factor as a decimal;
Q = design capacity;
R = period between reactivation in months;
S = volume of contactors in cubic feet;
V = variable impacting system cost;
X = operating cost variable; and
Y = dependent variable (O&M, capital or total unit costs).

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